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EMERGING ISSUE

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Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions

Sunwook Kim[1], Albert Moore[1], Divya Srinivasan[1], Abiola Akanmu[2], Alan Barr[3], Carisa Harris-Adamson[3,4], David M. Rempel[3] and Maury A. Nussbaum[1,5]
[1]Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA, USA;
[2]Construction Engineering and Management, Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA;
[4]Department of Medicine, University of California at San Francisco, CA, USA;
[5]School of Public Health, University of California at Berkeley, CA, USA;
[5]Virginia Tech – Wake Forest School of Biomedical Engineering and Sciences Blacksburg, Blacksburg, VA, USA

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*Corresponding author. E-mail: nussbaum@vt.edu

OCCUPATIONAL APPLICATIONS Work-related musculoskeletal injuries and disorders remain an important problem in the construction industry. Exoskeletons are an emerging wearable technology that assists or augments a user's physical activity or capacity. This technology is a potential solution to reduce the physical demands and fatigue experienced by construction workers and help improve worker safety, health, and performance. As a first step towards enabling exoskeleton use in construction, we captured the perspectives of construction industry stakeholders regarding adopting exoskeletons and continued use in practice. Stakeholder responses highlighted several important questions and concerns, which were grouped using qualitative content analysis into three categories: (1) expected benefits, (2) exoskeleton technology adoption factors, and (3) perceived barriers to use. Uncertainties were expressed about the practical value and usability of exoskeleton technologies, and the impact of this technology on worker safety. Given this, and the limited state of current evidence, we summarize important research gaps that need to be addressed in future for successful adoption and use of exoskeleton technologies in the construction industry.

KEYWORDS Exoskeleton, technology transfer, intervention, work-related musculoskeletal disorders, construction industry

INTRODUCTION

Workers in the construction industry continue to experience disproportionately high rates of work-related musculoskeletal disorders (WMSDs). For example, US construction workers in 2016 had a 11% higher rate of WMSDs than that for all industries combined (Bureau of Labor Statistics (BLS), 2018). The back and the shoulder were the most affected body parts, respectively accounting for 43% and 16% of all cases. Construction work is often inherently complex, involving substantial task variability and irregular work periods; repetitive manual handling materials or tool use, often in non-optimal postures; and working at a fast pace in a dynamic and often unstructured or unpredictable work environment (Dasgupta, Sample, Buchholz, & Brunette, 2018; Forde & Buchholz, 2004; Ringen & Stafford, 1996). These and other common aspects of construction work, such as organizational complexity, lead to substantial challenges for safety and health prevention research and practice in construction (van der Molen, Koningsveld, Haslam, & Gibb, 2005).

An exoskeleton is a wearable device that augments, enables, assists, and/or enhances physical activity (working draft terminology of ASTM F48.91 Terminology Sub-Committee). Exoskeletons are rapidly emerging as commercial products and present potential opportunities for preventing WMSDs by reducing physical demands and fatigue (de Looze, Bosch, Krause, Stadler, & O Sullivan, 2016; Kazerooni, 2008). Existing studies have demonstrated the efficacy of passive (i.e., without powered actuators) arm- or back-support exoskeletons during simulated occupational tasks (e.g., Abdoli-E, Agnew, & Stevenson, 2006; Bosch, van Eck, Knitel, & de Looze, 2016; Kim, et al., 2018a; Rashedi, Kim, Nussbaum, & Agnew, 2014; Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2017), and found reduced muscle activity, increased endurance time, and/or improved work performance. However, concerns have also been identified. For example, beneficial effects may be inconsistent between specific tasks or exoskeleton designs (Alabdulkarim, 2017; Kim et al., 2018b; Rashedi et al., 2014; Weston, Alizadeh, Knapik, Wang, & Marras, 2018). Exoskeleton use may also lead to the adoption of potentially riskier working postures to exploit the device support, such as favoring a more stooped lifting style (Frost, Abdoli-E, & Stevenson, 2009) or extended knee postures (Bosch et al., 2016).

Overall, however, exoskeleton use has potential, as an alternative workplace intervention approach, which may explain the recent growth of commercial industry exoskeletons in the market (e.g., exoskeletonreport.com). Given the complex nature of construction work, exoskeletons may be a particularly effective and novel control method to address the problem of WMSDs in this sector. Yet, exoskeleton use may also present unexpected safety and usability challenges. At present, evidence to support the safe and effective use of exoskeleton technology in construction is lacking. One best practice recommendation for the transfer safety and health technology into the construction sector is communicating with relevant stakeholders to better understand their industry-specific needs and concerns (Entzel, Albers, & Welch, 2007; Welch, Russell, Weinstock, & Betit, 2015). We thus sought to capture the perspectives of construction industry stakeholders about adopting and using exoskeleton technologies in practice, to facilitate future research and practice efforts in the application of exoskeletons to improve construction worker safety, health, and performance.

STAKEHOLDER AND WORKER PERSPECTIVES REGARDING EXOSKELETON ADOPTION AND USE

We completed semi-structured phone interviews with 26 construction industry representatives in two states (Virginia and California) to obtain their opinions and concerns about exoskeleton technology in construction. The study protocol was approved by the local Institutional Review Boards, and all participants gave informed consent. Interview questions were developed to elicit responses and discussion regarding: exoskeleton technology; expected benefits and perceived barriers about exoskeleton adoption and use in practice; potential use cases for future testing and investigation; and current safety and health practices (the complete interview script is available in online supplemental material, and was adapted from Kim, Nussbaum, & Gabbard, 2016).

Interviewees ($n = 26$) were employed at small- to large-size residential construction, building or heavy civil construction, and landscaping firms. Their positions included vice president ($n = 1$), project manager/engineer ($n = 11$), safety and health manager/director ($n = 6$), carpenters ($n=7$), and unspecified ($n=1$). Job experience of the interviewees ranged from 2 to 33 years (mean $=11.9$, $SD=9.4$). Prior to phone or in-person interviews, the interviewees were provided electronic versions of a consent form, interview question topics and brief descriptions and pictures of commercially-available arm- and back-support exoskeletons. Note that the interviewees were generally unaware of the existence of industrial exoskeletons prior to participating in the current investigation. Each interview session required $\leq$30 min and was transcribed either directly for phone or in-person interviews, or from audio recordings of the interviews.

To understand the perspectives of interviewees regarding exoskeleton technologies, a qualitative analysis was used. In this analysis, interview responses were loaded verbatim into NVivo® 11 qualitative analysis software (QSR International Pty Ltd.). The two investigators analyzed and coded three random transcripts using the codebook developed jointly by the graduate-student researchers and one of the authors following an iterative approach (Forman & Damschroder, 2007), and through communication between our two research groups (in VA and CA). After inter-rater reliability was assessed and verified, one investigator coded the remainder of the transcript. We used an inductive coding process, combined similar meaning codes into meaningful clusters, and identified emerging categories (Hsieh & Shannon, 2005). Figure 1 summarizes the structure of the categories and subcategories identified. Results in each category are presented in more detail below. Note that some direct quotes have been lightly edited to enhance clarity.

Expected Benefits of Exoskeleton Use in Construction

Productivity gain was a major expectation, as workers were anticipated to be able to perform tasks more easily and effectively since an exoskeleton can support/assist body postures/motions during tasks: "*it would help guys do the job faster, ... it would give them the ability to do their work easier.*" Given such support/assistance, most respondents (85%) expected that using an exoskeleton should help reduce musculoskeletal injuries and disorders, and further help retain workers: "[exoskeletons] *could help with back strains from lifting, twisting, and turning for sure.*"; "*you start making it easier on a person's body they can work faster, they could work healthier and they could work longer.*" Another participant reported that "*several construction workers complain about the long-term physical wear that construction has on their bodies - exoskeletons might help reduce that wear.*" Additionally, it was thought that exoskeletons could benefit those who have physical disabilities or injuries, so they could remain working. Yet, there were mixed expectations regarding whether exoskeleton use could help expand the size of their workforce, such as by retaining injured or older workers.

Perceived Barriers – Safety and Health Concerns

Several safety concerns were raised about wearing an exoskeleton at a worksite, including catch and snag risks, fall risks, hygiene issues, and a false sense of safety.

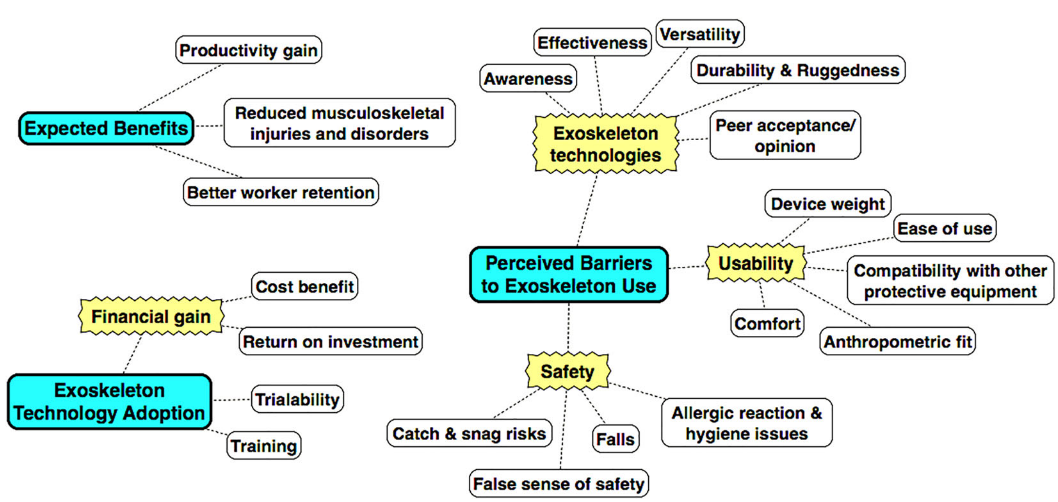

FIGURE 1 Summary of categories and subcategories regarding exoskeleton adoption and use in construction. Note that filled shapes are higher-level categories in the hierarchy, and the same color indicates the same hierarchical level.

For example, over half of the respondents (54%) suggested that wearing an exoskeleton may increase the likelihood of being caught in equipment or snagged on protruding/passing objects: "*When moving parts around, could the exoskeleton be caught in it*?" One of the interviewees mentioned that "*the device may get caught into heavy machinery and pull someone into harm's way,*" while another voiced concern about the possibility of "*getting electrical wire wrapped or caught in the arm supports.*" Given that construction workers often need to walk around in areas with surface hazards (e.g., muddy or uneven surfaces), concern was expressed that wearing an exoskeleton may challenge the balance of the wearer in hazardous walking conditions: "*you're around a lot of mud, you move around rough terrain, you might get into tough spots.*" Interestingly, one interviewee noted that workers may feel safer with an exoskeleton, and thereby may be prone to taking more risks or overworking: "*A little concerned that people are given a false sense and over doing it.*" Another interviewee noted that skin contact with the parts of an exoskeleton may cause allergic reactions or hygiene issues.

Perceived Barriers – Exoskeleton Technology and Usability Concerns

Regarding the actual exoskeletons, all the interviewees expressed practical concerns about ruggedness, effectiveness, versatility, and usability. Given that an exoskeleton is a wearable device used to augment, assist and/or enhance physical work activities, one interviewee questioned how using an exoskeleton would be accepted by coworkers, suggesting that using it may appear as a sign of "*weakness.*" Some (39%) suggested that the durability and ruggedness of an exoskeleton might be a potential barrier, especially because most construction work is performed outdoors in all-weather conditions: "*wears it for a few days and then joint breaks … and it breaks every month or every couple of weeks … they just won't use it.*" Related to the effectiveness and versatility of an exoskeleton, interviewees noted: "*Do people feel better at the end of the day?*"; "*You know* [exoskeletons] *would be brought in [to be] utilized. … A lot of work we do are kind of the same but kind of different.*"; "*It would have to be flexible and versatile enough to be adaptable to multiple situations.*"

Many interviewees (69%) indicated potential usability issues. Specifically, it was suggested that an exoskeleton may not be usable with other personal protective equipment (PPE), such as powered respirators and fall-arrest harnesses: "*if you are working at an elevated height, it could be that the exoskeleton comes into conflict with your harness.*"; "*being cumbersome to wear in certain applications … our employees are required in some applications to wear fall protection.*" Also mentioned was that using an exoskeleton may be uncomfortable or difficult, for example due to suboptimal fit to the anthropometry of a given construction worker population, by limiting range of body motions, or by impairing precise and smooth control of arm motions particularly with an arm-support exoskeleton: "*you've got to get the average person comfortable using it, the people who aren't in the greatest condition using it.*"; "*if they're doing sustained welding …* [exoskeletons] *have to be fine-tuned enough that small incremental movements can be controlled and supported and have to be smooth, not jerky.*" Some noted concern about the weight of an exoskeleton: "*the actual weight of the exoskeletons on the individual, how much and where is it putting pressure*." Additionally, there was a hesitancy expressed regarding whether using an exoskeleton might alter current work practices or require a long adjustment period: "*Currently held beliefs are if being so far from traditional methods, I see crafts and others will balk at being willing to use exoskeleton devices.*"; "*Getting used to the device is the biggest barrier - it's like having a bigger body.*"

Exoskeleton Technology Adoption Concerns

Initial investment costs and some certainty regarding cost-benefit and return-on-investment (ROI) were indicated as the most important factors in decision-making for the adoption of workplace technology in general. A majority of the interviewees (77%) noted the importance of initial investment costs of adopting exoskeletons in particular: "*Cost is always the most important, so if you make cost a lot you may not buy it*"; "*the cost is the biggest hindrance for us.*" Noted benefits were financial gains (e.g., improved productivity, reduced costs associated with injuries/disorders), and which should be able to justify the cost of an exoskeleton: "*we're willing to look at anything that's going to make us more productive, more profitable, and keep the quality that we expect in the field.*"; "*At the end of the day, it always circles back around to financial benefit.*" Nearly half of the interviewees also suggested the importance of a rapid ROI. In addition, many respondents (69%) indicated a need for effective training materials and personnel for exoskeleton technology: "*having a training program or orientation program would be kind of the biggest way to get people behind the idea of using the exoskeleton*"; "*have to have someone with a lot experience in* [exoskeletons] … *to answer all the questions that are going to be had.*" Several interviewees (39%) also suggested that workers should be able to try out exoskeletons in advance: "*have them use it and demo it.*"; "*People to be more behind it and allowing them to go out for a couple of hours on the job or a day and use it.*" Interestingly, laborer interviewees voiced concerns that the cost of the device would be the biggest barrier to its implementation, while some managers noted that acceptance and use by workers would be the biggest barrier.

Potential Exoskeleton Use Cases

The interviewees indicated that exoskeletons may be beneficial for tasks involving heavy material handling, overhead work, use of heavy tools, or repetitive tasks: "*any application where you hold a tool and do a repetitive motion away from your body*"; "*It could help reduce over-exertion, as far as lifting boxes, repetitive motion*" Specifically, the suggested tasks included: carrying and lifting, use of tools for concrete work (e.g., finishing, chipping using a jackhammer or a rivet buster), tile installation, brick laying, grinding, painting, and tasks involving overhead work (e.g., hanging drywall, wiring, bathrooms). The interviewees also indicated other industries that would benefit from exoskeletons and listed examples such as tree trimming, tasks performed by iron workers, and auto assembly. One mentioned that all construction workers receiving physical therapy for injuries should be provided an exoskeleton.

RECOMMENDED FUTURE RESEARCH REGARDING EXSOSKELETON USE IN CONSTRUCTION

Responses from experienced construction professionals show important research gaps that should to be addressed for successful adoption of exoskeleton technologies in the construction industry. Uncertainties about the practical value (i.e., effectiveness and efficacy) and usability of exoskeleton technologies, along with unclear impacts on worker safety and health, were the most prevalent concerns identified. To resolve these uncertainties, we encourage future research in several areas summarized below. Note that some of these areas are likely also relevant beyond the construction industry.

- *Assess the short- and long-term effects of different exoskeleton technologies in terms of worker safety and health, acceptance/trust, usability, and work performance*: Evidence to date is limited on the short-term consequences of using an exoskeleton (e.g., Abdoli-E et al., 2006; Bosch et al., 2016; Kim et al., 2018a; Rashedi et al., 2014; Spada et al., 2017). Figure 1 can be of benefit to inform specific future research areas, such as the impact of using an exoskeleton on fall risk, usability, and exoskeleton effectiveness with respect to different worker characteristics (e.g., age, sex, obesity). To guide device selection and effective use, systematic comparative and/or prospective investigations are recommended.
- *Determine the task- or job-specific benefits and limitations of an exoskeleton*: One perceived barrier regarding exoskeleton technologies is effectiveness (Fig. 1), and we believe that the effects of an exoskeleton will depend on the specific task demands and work conditions. For example, earlier studies have found inconsistent effects of the same exoskeleton when used to complete different tasks (Alabdulkarim, 2017; Rashedi et al., 2014; Weston et al., 2018). To guide device selection for a given task/job, there is a need to understand the effects of different aspects of exoskeleton design (e.g., device mass, support mechanisms) and how these interact with specific task characteristics (e.g., work pace, precision requirements, postural demands, level of mobility, tool use, environment) and worker characteristics.
- *Assess the compatibility of different exoskeleton types with relevant personal protective equipment (PPE)*: In practice, workers often need to use some PPE (e.g., fall arrest harness, powered respirator, special protective clothing). Since an exoskeleton is wearable, it may interfere with PPE (usability subcategory in Fig. 1). Information is thus needed on best practices/

recommendations for exoskeleton use with PPE and what design changes may be needed to current-generation exoskeletons and PPE.

- *Develop training modules for exoskeleton use*: To promote the safe and effective adoption or diffusion of exoskeleton technologies (exoskeleton technology adoption category in Fig. 1), usable and effective training modules are needed for, e.g., workers and supervisors. These training modules should be designed to provide comprehensive information on safe usage, benefits, limitations, and safety concerns. Training methods should be tailored to accommodate diversity in construction, such as related to language, sex, anthropometry, age, and work experience. Furthermore, training modules may need to address best methods for acquiring new work practices if exoskeleton use requires a change in work practices.
- *Obtain empirical evidence to support cost-benefit analyses of exoskeleton use*: Potential benefits of different exoskeleton types need to be translated into direct and indirect financial gains through case studies, which can help develop a cost-benefit analysis tool or provide empirical evidence for justifying exoskeleton use (see exoskeleton technology adoption category in Fig. 1). A clear and rapid ROI was noted of particular importance among the participants, consistent with prior reports on safety and health technology adoption in construction (Entzel et al., 2007; Welch et al., 2015).

The recent advancements in and availability of industry exoskeletons offer new approaches with the potential to advance work ergonomics and performance in construction. However, realizing this potential will require addressing many practical concerns regarding safety, health, and usability, and considerable research efforts from both researchers and practitioners alike. With such efforts, and the resulting improved knowledge regarding exoskeleton use in construction, we may see exoskeletons becoming another useful tool in the construction worker's toolbox. Or, perhaps even a type of construction clothing that enhances workers' productivity and satisfaction, especially if soft (e.g., textile) exoskeleton technologies become more mature and affordable (Asbeck, De Rossi, Holt, & Walsh, 2015; Dinh, Xiloyannis, Antuvan, Cappello, & Masia, 2017).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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ORCID

Sunwook Kim http://orcid.org/0000-0003-3624-1781
Albert Moore http://orcid.org/0000-0003-2930-5097
Divya Srinivasan http://orcid.org/0000-0001-9327-6177
Maury A. Nussbaum http://orcid.org/0000-0002-1887-8431

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